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TRANSIT ANEMOMETER TRIALS AT THE CAMBRIDGE WHITTLE LABORATORY

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Summary

The Rolls-Royce Transit Anemometer was applied to several rigs in the Whittle Laboratory. These included a 14" calibration jet, to demonstrate the intrinsic accuracy of the machine, and a static turbine cascade in which mid span traverses were produced of the entire duct and a boundary layer. Both these plots accorded well with previous data and were very much more easily obtained.

Data from a rotating cascade was encouraging. Firstly some measurements were made upstream without time gating and shown to yield, with some processing, results similar to time resolved data. Interblade traverses were made at different heights and a downstream boundary layer traverse was obtained. The main problem is location of the sampling point with respect to the rig for measurements near walls.

The demonstrated versatility of the present transit anemometer makes it a powerful tool for investigations of aerodynamics in turbomachines. There is now no question of its feasibility and ease of use and comprehension. Opportunities are being sought to apply this technique to higher speed machinery more representative of aero engine components.

1. Introduction

This laser anemometer has been produced to meet the present and some future requirements for non-contact optical measurement of velocity fields in many research turbomachine applications. To this end it must be demonstrated as a mobile, versatile and easily used technique and the results presented here go some way towards this. The data so obtained must be compatible with current and future design parameters and it will be obvious from this note that this tool may be used in a variety of ways and the data presentation format tailored to those requiring the measurement.

A brief description of the machine is appropriate. A 15mW Helium Neon laser is focussed to two small intense spots separated by a known distance ($\sim 664\mu m$ in this report). Light scattered from small particles entrained in the flow is collected and analysed with a high speed 'Malvern' digital correlator to yield estimates of particle velocities. This system has important differences from the now conventional and widely used fringe systems in that it has a capacity to reject a higher proportion of unwanted scattered 'flare' from surfaces near the region of interest. This advantage confers the ability to make useful surveys in rotating blades. The price of this advantage is that more particles must be provided to obtain measurements to a given accuracy. Once this price is paid however the measurements will yield more flow properties more easily i.e. you need more data, but when you get it, it is also more complete and you may do more with it.

The system operates in backscatter with the attendant ease of traversing and the spots are rotated using an optical rotator. Although the procurement of this component may be difficult the advantages it confers are indisputable. The alternative spot rotation methods have serious disadvantages. With separate rotation of output and input optics it is difficult to use an optimum field stop flare filter and with rotation of the total assembly the mechanical problems can become serious. The system used here allows sufficient rotation of the spots to change their relative positions about either a vertical or a horizontal axis and will traverse the sampling point over a 9 inch cube to .001 inch.

The time window has a 1μs resolution both in duration and on time of start after trigger. Repeatability is much better than this if the trigger is good enough.

2. Logistics

The anemometer is dauntingly large because of the need for a rigid support for the traverse assemblies (x, y, z; 9 inches each) but this may be separated from the optics and transported separately. The traverse probably weighs less than 400Kg and on a level surface is easily moved on its own wheels by one man. It may be conveniently handled by a fork lift truck, crane or gentle ramp and may be moved by usual methods without technical accompaniment. The optical assembly and all the electronics and supporting bits and pieces fit easily into a 15cwt van. Reassembly takes about one man hour and some knowledge, but no special skill. If the optical head is handled more roughly than might be desired (it does not like to be dropped from too great a height) optical realignment takes a few seconds but very considerable expertise. This difficulty will be obviated in later marques.

The transit anemometer is described in RR(OH)632 and discussed in terms of its instrumental broadening in RR(OH)638 but as more experience is gained with the equipment the presentation and relevance of the information will be improved.

3. Particles

Particles must be provided for this type of anemometry and in the absence of natural particles we used a Norgren oil mist lubricator producing particles around 2~4μm diameter. The oil we chose to use was a low viscosity compound used in theatrical smoke generators to avoid toxicity problems. In the event so small an amount was used that it was not even detectable by smell in the Cambridge laboratory. The cascade with a 5 square foot output area was adequately seeded by about 10ml per hour, and measurements would have been possible but more tedious at a lower rate than this. Other seed generators, such as one recently produced for the dispersal of inhalants for asthma sufferers, are being investigated. They are said to be very cheap, and seem quite good.

4. Some Applications Results

4.1 Calibration Jet

To give some confidence in the intrinsic accuracy of the anemometer it was applied to a 14" open jet used for calibrating other transducers, e.g. hot wires. It was of low turbulence and it was only the measurement of mean flow which was required here. Fig. 1 shows a plot of speed derived from a standard pitot plotted against the speed measured by the transit anemometer, albeit a little further downstream.

The anemometer measurements were interpreted by reading the correlator output from an oscilloscope screen and interpolating between digitally displayed points, not the most accurate way of deriving this data but quick and easy: both of which are highly desirable.

The root mean square discrepancy was 0.3% from each of two runs and there was no significant bias to high or low systematic error over both runs. In view of the use of the simple interpretation method i.e. measuring the peak transit time and dividing into the spot separation (itself difficult to measure to better than a small fraction of one percent) these data were felt satisfactory. This method of processing is only appropriate for very low turbulence as skewing bias can be troublesome for high levels, necessitating more elaborate data processing.

Fig. 2 shows a vertical traverse across the centre part of the jet using the pitot reading as a normalisation factor. Only the centre 9 inches were easily accessible without bulk movement of the anemometer, itself designed for application to smaller systems. Note that the ordinate is in percent difference from centre line pitot measured velocity and that the transit anemometer measured velocity tends to be higher. This may not be significant and certainly would suggest that the jet profile is far from bad.

4.2 Turbine Cascade

Fig. 3 shows data from a static cascade of turbine blades. The span was 460mm and the chord about 155mm, making Fig. 3 approximately size. The measurement stations were all at mid span and at the root of each marked vector. The approximate scale of vectors is 6mm = $10ms^{-1}$ and the angles are as marked with respect to the cascade. The rig operating condition was position 4 on the motor control with the throttle wide open. The static pressure in the plenum was 2.30" water at a Barometric pressure of 29.45" Hg and a temperature of 292K. No attempt was made to hold the rig to an exact condition and small variation due to fluctuating mains voltage can be discerned in the results. This in no way invalidates the purpose of the measurements and it would have been unnecessarily time consuming to trim the rig for each measurement.

Table 1 records the data from which Fig. 3 was plotted as it represents a higher accuracy than is immediately apprehended from the diagram. The points are identified by a row number and the number along that row starting from the numbered end. The direction is identified with the inlet direction and represents the degree of turning imposed by the blades at that point.

A number of interesting features is to be observed. For example the amount of turning is not monotonic along a line at right angles to mean velocity, that is the mid stream region is less turned than that near the edges. The velocity is much lower near the pressure surface as expected until the exit plane where uniformity of profile is much improved. There is evidence of separation about half way along the suction surface, both in directions and in proportionally reduced local average velocities. Although it was not the purpose of this exercise to measure turbulence an incidental observation of this showed a significant increase at points 5.6, 6.4 and 7.6 compared with points 2.2 and 4.4 which again indicates separation (so did wool tufts fixed to the adjacent blade in the cascade!). Other points did not have the turbulence recorded.

Although accurate measurement of turbulence is possible with this technique this was not done here as other measurements were more pressing. It should be noted that the entire array of measurements here was obtained in less than two hours, including the calculations with the aid of only a hand calculator.

To explore other regions of the cascade some simple tests were performed. The end wall through which all observations were made was of rather scratched perspex and represented the worst window conditions in which this device has been used. Good velocity measurements could be obtained 10mm from this wall with careful orientation of the anemometer head to avoid the worst specular reflection. A good glass window would allow this distance to be reduced significantly. Measurements were obtained closer than this but something more suitable than perspex must be used if these measurements must be guaranteed.

A more critical test was to see how far measurements could be made into a boundary layer. Fig. 4 shows the result of traversing the sensitive region of the anemometer towards the wall. In fact, of course, the points were observed in random order to minimise any chance of systematic errors. The main difficulty with this type of measurement is obtaining the exact location of the wall. In this case maximisation of photo-multiplier overload gives a fairly consistent estimate of where we think the wall is, but it would be better to define a good method of identifying the wall. The station at which the boundary layer was measured is marked A on Fig. 3 and although the actual traverse was not quite normal to the surface it has been corrected to appear so - boundary layer growth is not so rapid as to cast doubt on this procedure.

This anemometer will also measure the angle of the wall at contact. It was 51.5° to the inlet direction. The closest to the wall which we would claim here is 100μm but since the present machine was not even designed with this in mind it was good that it could achieve this so easily.

The thickness of this boundary layer was compatible with earlier measurements made on this same cascade and very plausible when compared with calculation. Unfortunately this particul · situation is not simply analytic (Ref. 3) and no attempt has been made to go into detailed calculation.

4.3 Rotating Machine

Measurements were made on the Oxford Rig Fan Rotor at several stations. The first data were obtained 0.75" upstream of the leading edge 5" from the outer wall. The rig was run off design conditions with a flow coefficient of 0.45, not very far from stall. In the initial series of runs no trigger was available from the blade and the observation data was accumulated over all time. As the angle of spot orientation was varied the correlogram showed one or two peaks. Fig. 5 shows the velocities observed from these peaks. This picture is consistent with the velocity varying its magnitude and direction in some periodic way. If we make some further assumptions that the periodicity is constant and construct the velocity time probability shown in Fig. 6 we may attempt a waveform reconstruction. The data of Fig. 6 are derived from the areas of the peaks of the correlogram with the background removed corresponding to each angle. In each case they have been normalised by the mean count rate and a crude correction for sampling bias has been made on the incompressible assumption: each probability estimate was corrected by dividing by the local velocity magnitude.

The data in Fig. 6 may be associated with the velocity probability or on the assumptions just stated the time for which a given velocity prevails in each cycle. The height of each point in Fig. 6 may be used as a phase increment and the total phase orbit normalised to 360°. The actual values may be scaled by the measured angles to give axial and tangential velocity components and are plotted in Figs. 7 and 8 against arbitrary phase.

At a later date a time pulse became available to identify each blade passing and we were therefore able to plot new velocity data in a laboratory frame with a fixed phase reference to the rotor. If we make the plausible assumption that the periodicity of the earlier data was the same as that of blade passing then we may

compare the two data, Fig. 7 and Fig. 8. The degree of correspondence is good when considered in the light of the method of obtaining the phase reconstru ted data. The tangential fit is worse than the axial as is expected from the sensitivity to measurement uncertainty.

When the 'once per blade' trigger became available measurements were made inside the blade passage in rotor co-ordinates. The same condition was measured, again fairly near stall. This is shown for a plane 0.5 inches behind the leading edge and 5 inches from the tip. Rotor speed was 520rpm giving 5.24ms per blade passage and a velocity of $34.5 ms^{-1}$ at the measurement station. This value was used for transformation into rotor co-ordinates. The vector plots at upstream and downstream of leading edge stations are shown in Fig. 9.

The rotor was hereafter operated near its design condition, i.e. with a flow coefficient of 0.7 and the upper half of Fig. 10 may be directly compared with Fig. 9 at the lower condition. The station and gating conditions are the same. The other panel of Fig. 10 shows the analogous traverse at a new radius of 29 inches - 1 inch from the blade tip. Only small differences are to be observed - not surprisingly. Fig. 11 shows a similar traverse at 0.6 inches from the tip where there is significant effect from the tunnel boundary layer. The profile is now seen to be different and the turbulence is increased.

The nature of this turbulence increase was recorded by taking measurements at several angles clustered around the mean velocity direction and reducing those with a simple computer program designed to obtain a velocity probability vs. velocity plot for each angular orientation, together with some appropriate normalising quantities and statistical properties. These data are summarised in Table 2. Obvious from this is the non-isotropic nature of the turbulence at this station. The axial fluctuation is rather less than twice the tangential near the blade passage centre but the tangential component increases significantly near the blade on both sides. This is a complicated region as the measurement station is within the tunnel boundary layer at this radius.

The right hand diagram on Fig. 11 shows the inlet velocity 1.3 inches upstream of the leading edge. On this figure the velocity direction is not significant but the axial turbulence is shown once more to be similar at all parts of the cycle. The mean speed averaged over the blade passing cycle is 19.0ms^{-1} at +0.6^{o} to the tunnel axis measured positive in the direction of blade rotation, which convention is observed throughout. Averaged over a full cycle the axial turbulence is 8% and the tangential component is 15% but these are comprised of the true 'turbulence' in the proximity of the boundary layer and the 'unsteady' but periodic variation associated with blade passing. These could be separated by gating once per revolution to eliminate any effects of blade to blade variation. On the assumption of identical blades and mounting the educted turbulence is almost invariant under rotor station at 6.5%. The three contributory effects may therefore be isolated with reduced data collection efficiency by taking ensemble averages over each blade or all blades at selected times after transit or taking time linear averages and separating spectral data by deconvolution.

A radial survey of the duct boundary layer 1.5 inches downstream of the trailing edge yielded Fig. 12. This is a comparison of mean axial velocity measured by a pitot and transit anemometer. In fact the mean flow direction was +12^{o} to the tunnel axis in the direction of rotation. The abscissa scaling is a simple normalisation by free stream velocity out of the influence of the boundary layer. The very good fit shown was obtained by assuming that the wall was 2.0mm away from where we thought we had measured it to be. This is not too iniquitous a thing to do as the resolution of the instrument is not really appropriate for measurements at right angles to the boundary layer and it is claimed to be no better than 2.0mm in this direction. However it illustrates the very important property of knowing exactly where the measurement point is - a problem common to most optical techniques. It is possible to be much more precise in location of the measurement point but this can be very tedious and requires great care and a good deal more thought must be given to this topic.

A final series of observations was made 1.5 inches downstream of the trailing edge 0.6 inches in from the tip and these observed the efflux directions and turbulence as a fluctuation of speed in this direction. Fig. 13 shows this plotted in laboratory co-ordinates so the blade trailing edge reference is a horizontal line on the figure. The turbulence at the wake increases to nearly 18% whilst that near the mid passage is around 6% with the relatively uniform 8% elsewhere.

5. Discussion

From the fourteen brief experiments outlined here it is clear that here is a new and versatile tool for the aerodynamist and designer of rotating machines. In the Cambridge environment it has shown its potential for making accurate measurements rapidly, easily and with very little special skill. Interpretation of the correlogram may be performed, with no more than an oscilloscope and small hand calculator, to the accuracy and with the immediacy required for a large proportion of investigations. In other cases more sophisticated computer processing is available as needed. The instrument is available and workable now without further development but there are naturally improvements to be made which will extend its capability and improve the format of output data. It now seems desirable to have more than one output lens as the applications are beginning to demand both larger and smaller scale applications and a better optimisation may be reached for these by the change of one component only.

6. Conclusions

1. The complete transit anemometer may be moved from one site to another with very little fuss, and no unreliability has been encountered.

2. Many different types of velocity measurements may be made simply and rapidly to better than $\pm$ 1% accuracy on speed and $\pm$ 0.5° on direction, depending somewhat on turbulence.

3. Doping the flow at levels which are quite acceptable as laboratory ambient conditions yields measurements to the above specification in less than 1 minute per point for the sort of well behaved flows investigated here.

4. Measurements may be made within 100μm of walls parallel to the optical axis and better than 10mm of a poor perspex window nearly normal to the axis.

5. Measurements may be made within the blades of rotating machines and may be time gated to select individual blade passages or averaged over all blade passages at a particular station or set of stations in rotating co-ordinates.

List of Experiments at Cambridge

1. Comparison with pitot in the centre line of a laminar jet. (Fig. 1)

2. Traverse of centre area of laminar jet. (Fig. 2)

3. Mid span survey of turbine blade cascade. (Fig. 3)

4. Boundary layer traverse on pressure surface of turbine blade. (Fig. 4)

5. Test of window proximity nearly normal to optical axis

6. Rig Rotor 5 inches from tip 0.75 inches ahead of leading edge without gating away from design condition (Figs. 5, 6)

7. Same point and condition with time gating. (Figs. 7 & 8)

8. 5 inches from tip, 0.5 inches from blade leading edge. (Fig. 9)

9. As above at design condition. (Fig. 10)

10. As above but 1 inch from tip. (Fig. 10)

11. As above but near 0.6 inches from tip (Fig. 11) with turbulence (Table 2).

12. Near 0.6 inches from tip 1.3 inches upstream with time gating.(Fig. 11)

13. Boundary layer traverse 1.5 inches downstream of trailing edge. (Fig. 12)

14. Boundary layer direction resolution and turbulence measurements. (Fig. 13)

List of Figures

No.	Title
1.	Centre line Velocity in Calibration Jet.
2.	Calibration Jet Traverse.
3.	Velocity Vectors in Turbine Cascade.
4.	Boundary Layer Traverse at 'A' (Fig. 3)
5.	Peak Velocities.
6.	Velocity Probabilities.
7.	Velocity 0.75" upstream of Leading Edge (Axial).
8.	Velocity 0.75" upstream of Leading Edge (Tangential).
9.	Passage Traverse 5" from Tip, Away from Design.
10.	Inter Blade Traverses at Design.
11.	Measurement Near Tip at Design.
12.	Boundary Layer Traverse.
13.	Gated Velocity Traverse with Turbulence.

Reference

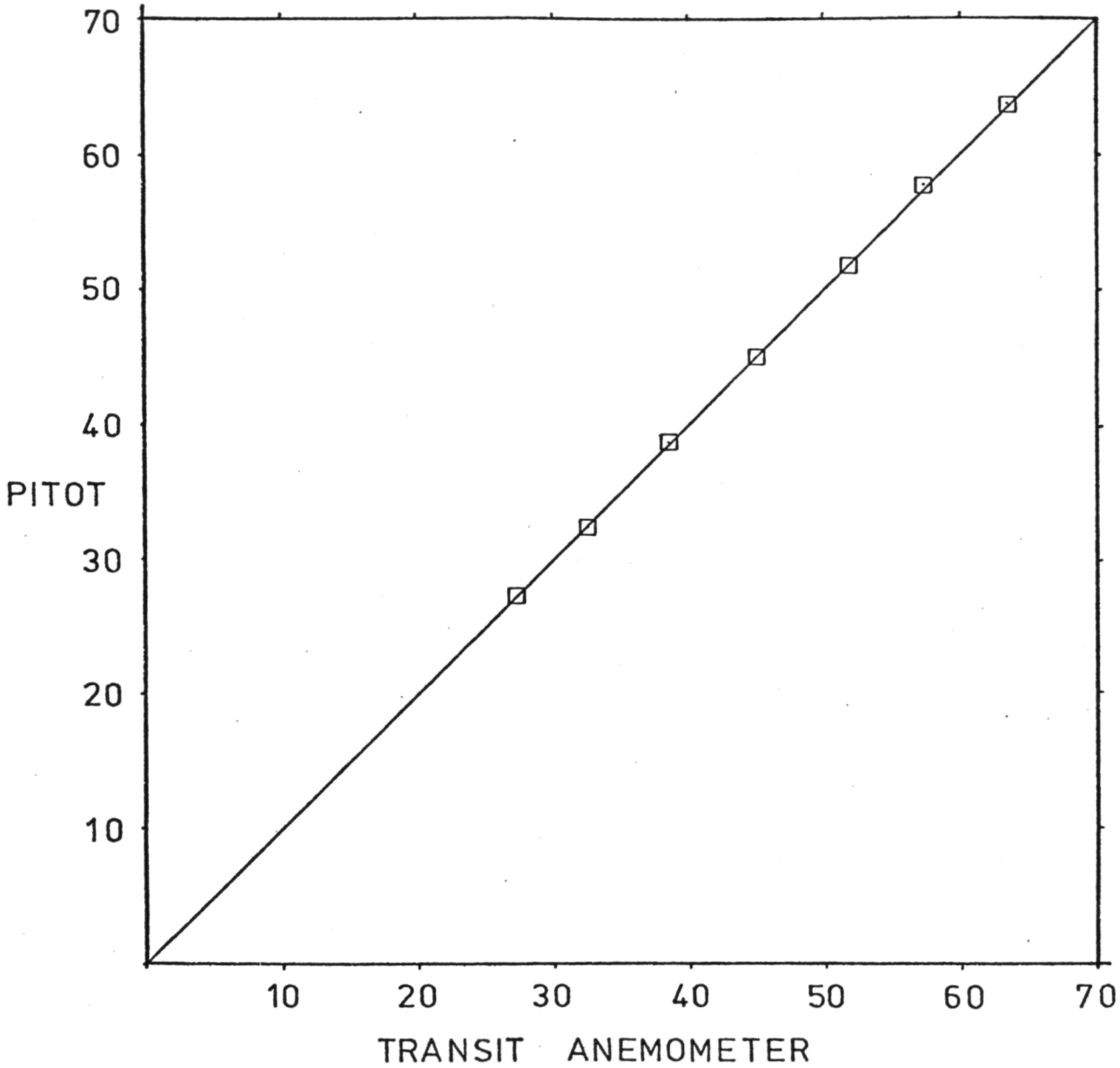
1. Schlichting H.
Boundary Layer Theory.
McGraw Hill Book Co. 1968.

TABLE 1 Velocity Vectors in Turbine Cascade (Ref. Fig. 3)

Point Row/No.	Speed ms^{-1}	Direction ^{o} of Turn
1.1	39.5	12.5
2.1	22.4	31.0
2.2	26.9	30.0
2.3	31.9	30.0
2.4	37.1	29.0
2.5	43.7	26.0
3.1	19.5	46.0
3.2	22.8	44.0
3.3	26.1	44.0
3.4	30.9	43.5
3.5	36.1	45.5
3.6	37.1	45.5
4.1	20.5	57.5
4.2	23.8	56.8
4.3	27.6	56.0
4.4	31.5	57.5
4.5	36.5	58.5
4.6	42.2	63.5
5.1	23.3	69.5
5.2	27.1	67.0
5.3	30.6	66.0
5.4	33.1	67.0
5.5	35.3	72.0
5.6	36.5	78.0
6.1	30.2	74.0
6.2	31.2	70.5
6.3	32.4	71.0
6.4	33.2	73.0
6.5	33.0	78.0
6.6	31.6	82.0
7.1	32.4	69.0
7.2	31.8	71.0
7.3	31.9	73.5
7.4	33.2	76.0
7.5	32.2	76.0
7.6	31.5	79.0

TABLE 2 Turbulence Within Blade Row near Tip

Point No. (See Fig. 11)	Mean Speed ms^{-1}	Angle From Inlet in Lab. Co-ord. degrees	Axial Turbulence % rms	Tangential Turbulence % rms
1	22.0	-10.5	5.9	5.7
2	22.3	- 4.0	6.2	3.9
3	22.2	- 0.5	5.5	3.9
4	21.1	+ 5.5	5.8	3.3
5	20.1	+ 9.5	6.5	3.4
6	19.6	+14.0	5.0	4.6



$\underline{\text{\textcircled{C}}}$ VELOCITY IN CALIBRATION JET. ms^{-1}

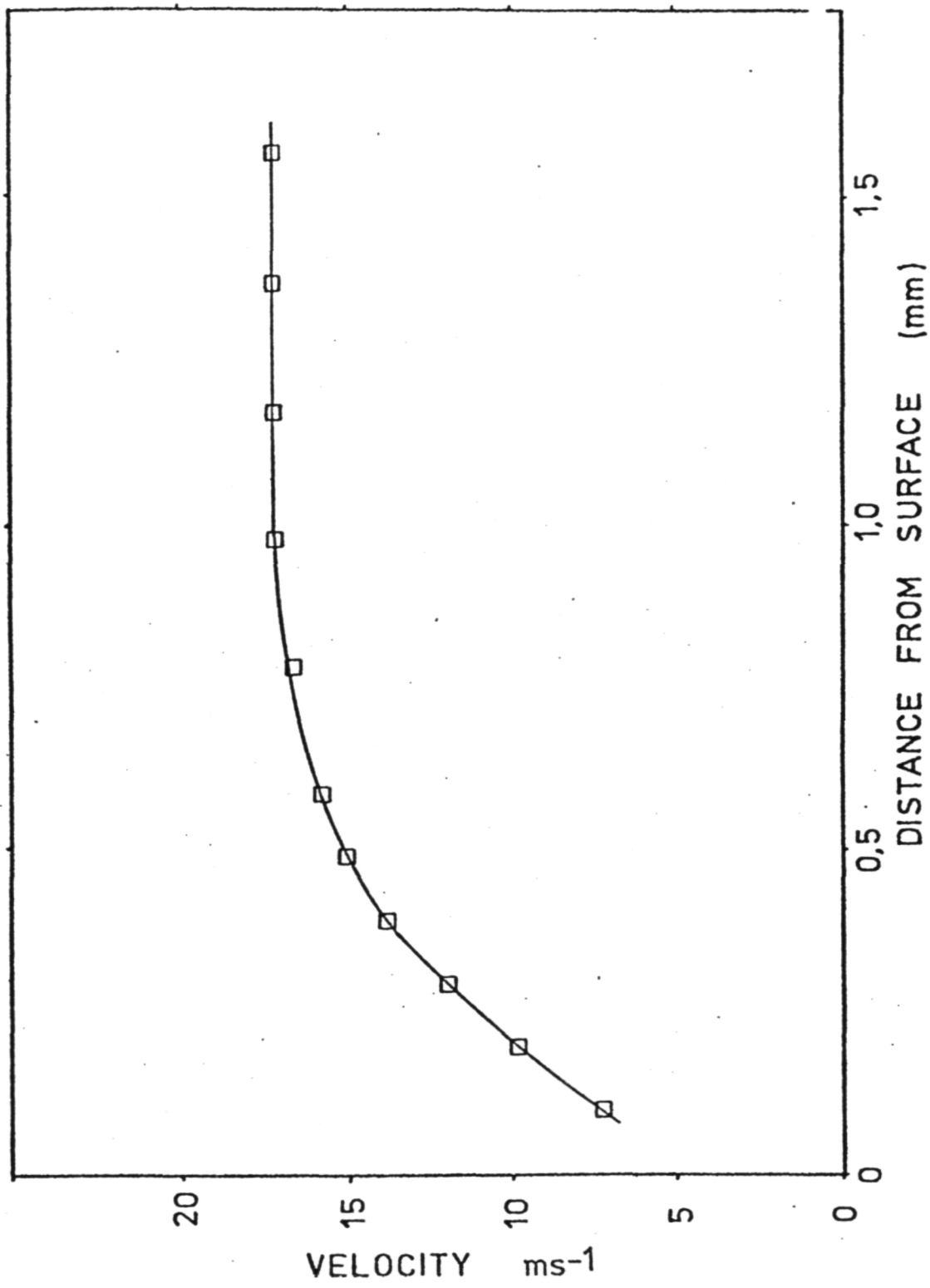
Fig 1

CALIBRATION JET TRAVERSE

Fig 2

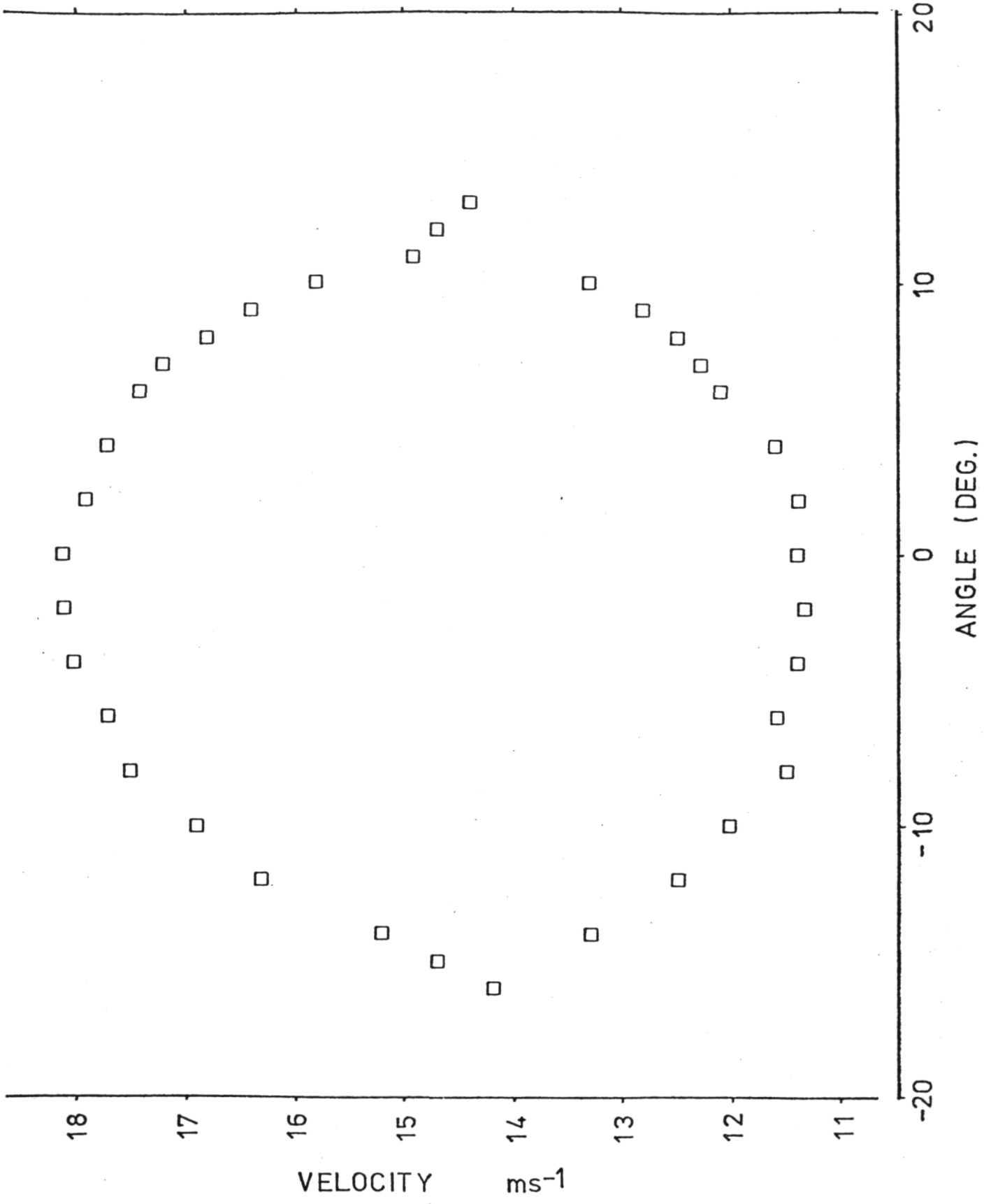
VELOCITY VECTORS IN TURBINE CASCADE 6mm = 10 ms^{-1}

Fig 3



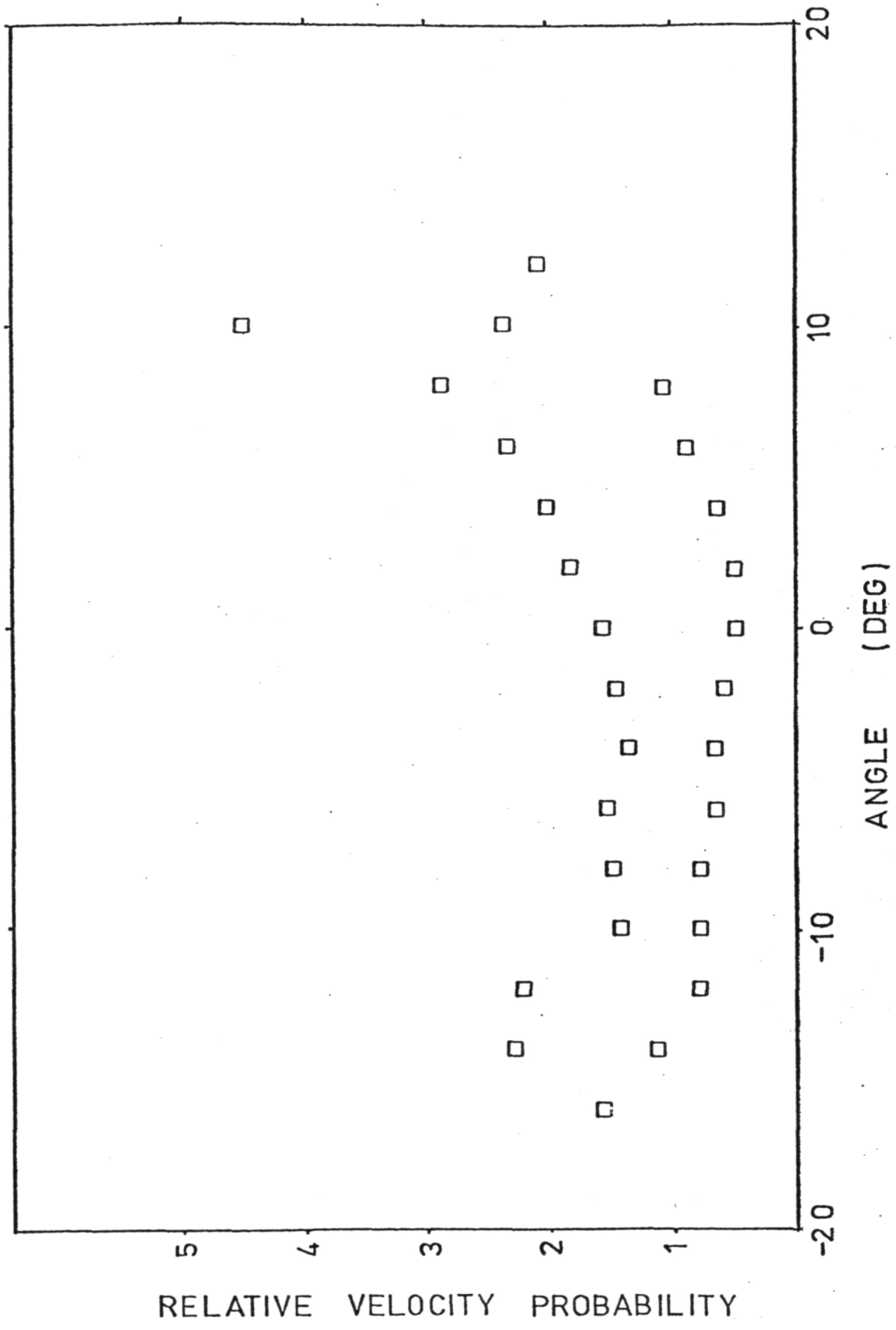
BOUNDARY LAYER TRAVERSE AT Ä (Fig 3)

Fig 4



PEAK VELOCITIES

Fig 5



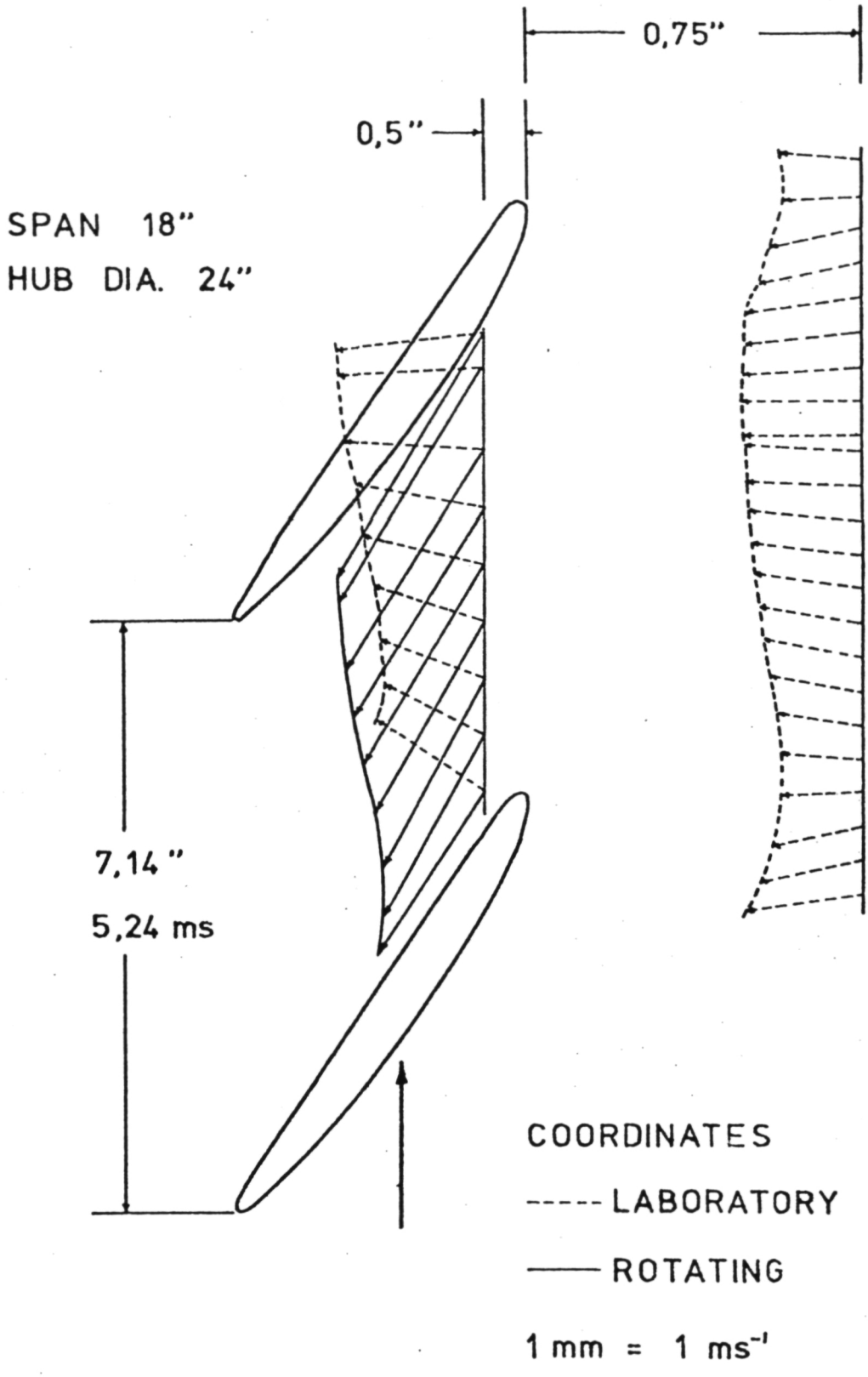
VELOCITY PROBABILITIES

Fig 6

VELOCITY 0,75" UPSTREAM OF L.E.

Fig 7

VELOCITY 0,75" UPSTREAM OF L.E.



PASSAGE TRAVERSE 5" FROM TIP

AWAY FROM DESIGN

Fig 9

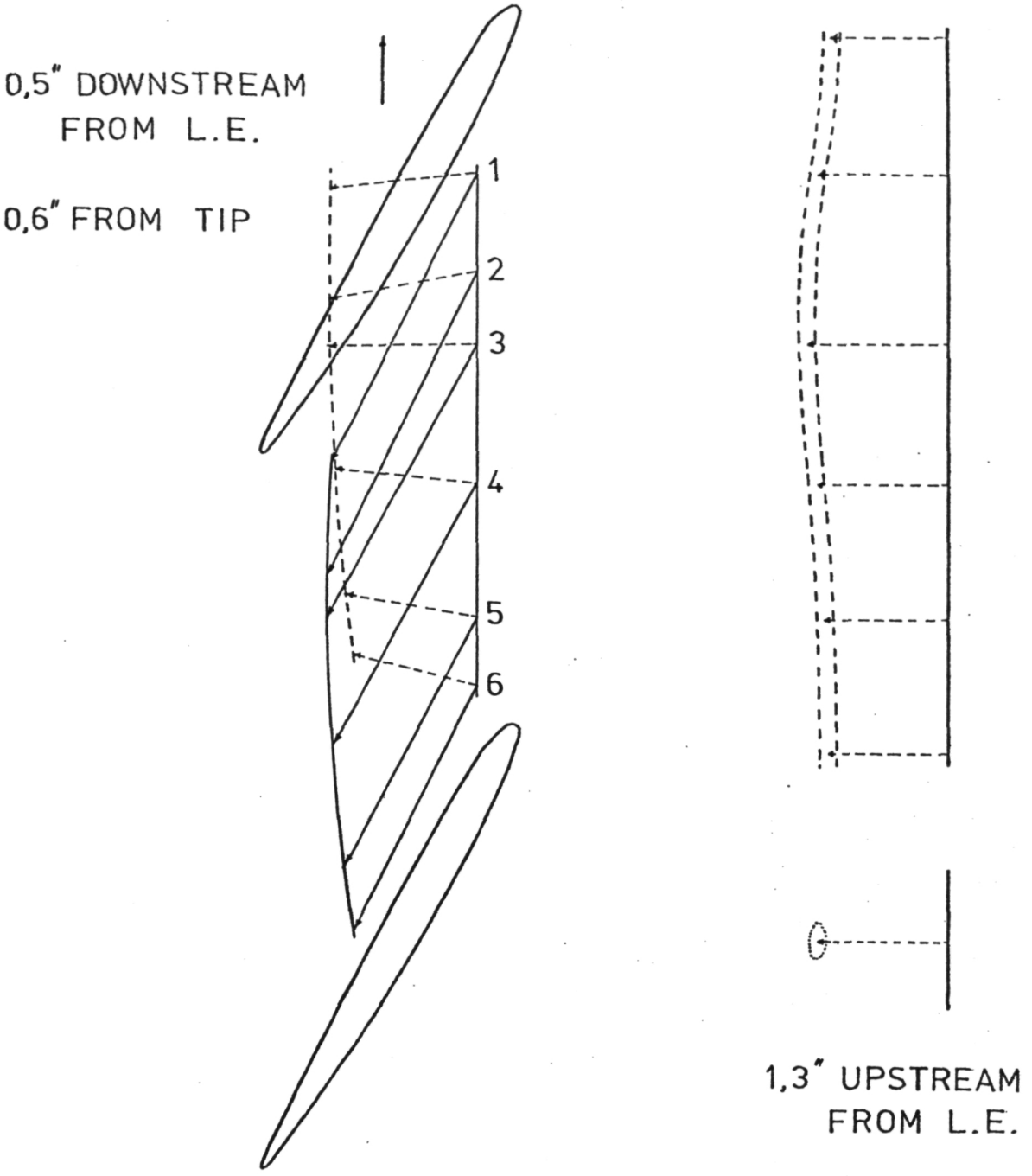
INTER-BLADE TRAVERSES AT DESIGN

COORDINATES

------ LABORATORY

—— ROTATING

Fig 10



COORDINATES

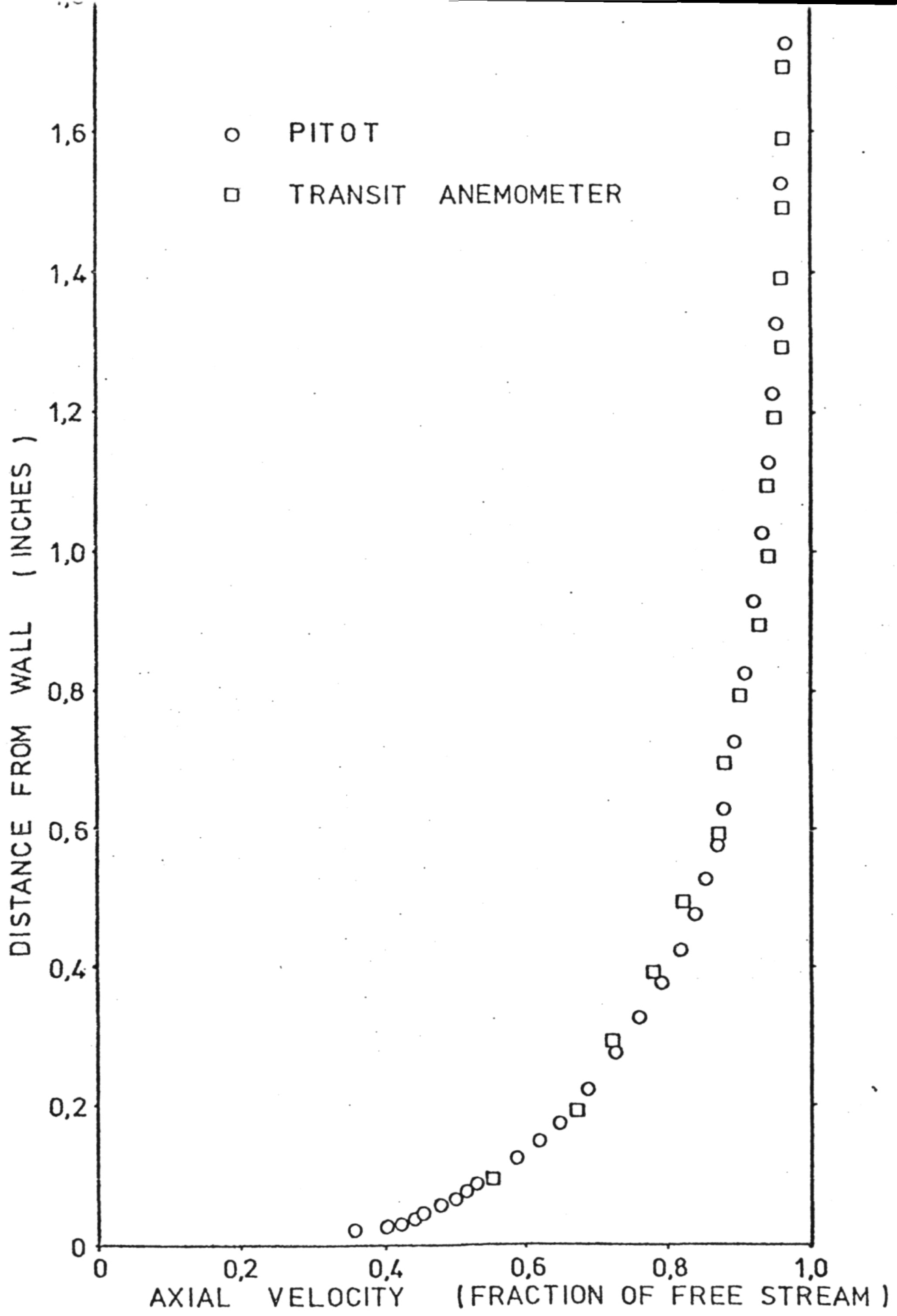
----- LABORATORY

—— ROTATING

MEASUREMENTS NEAR TIP AT DESIGN

(See text and table)

Fig 11

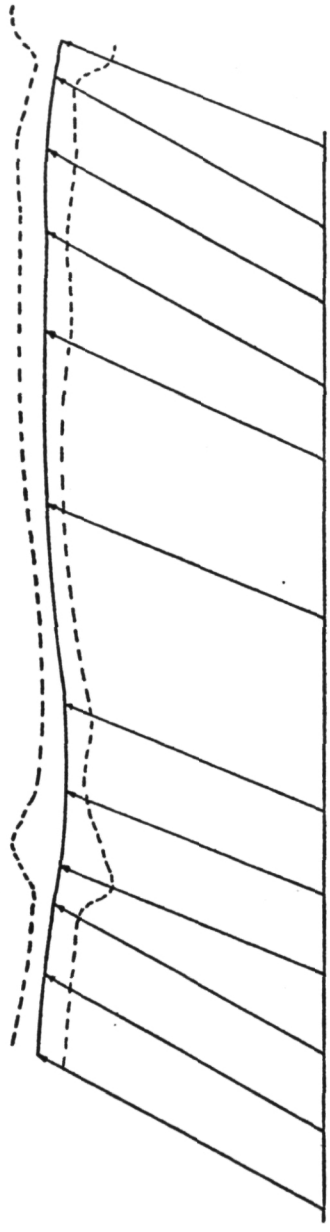


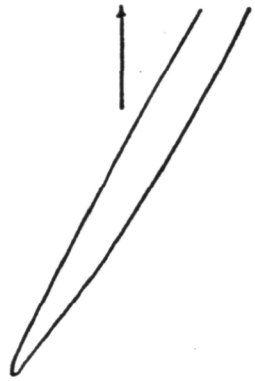
BOUNDARY LAYER TRAVERSE

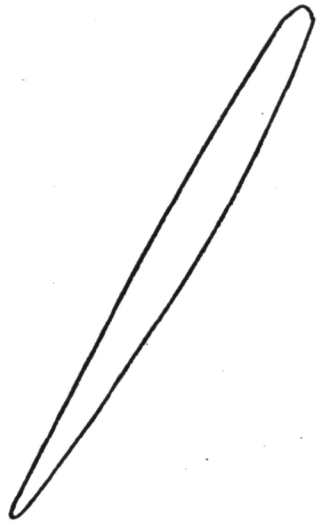
Fig 12

LAB. COORD.

2 mm = 1 ms^{-1}







1,5" DOWNSTREAM
FROM T.E.

0,6" FROM TIP

GATED VELOCITY TRAVERSE WITH TURBULENCE

Fig 13